COMPARISON OF SEISMIC TESTS ON URM PIERS AT HALF-AND FULL-SCALE

S. Petry[1] and K. Beyer[2]
[1] PhD student, Earthquake Engineering and Structural Dynamics Laboratory (EESD), School of Architecture, Civil and Environmental Engineering (ENAC), Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland, sarah.petry@epfl.ch
[2] Assistant Professor, Earthquake Engineering and Structural Dynamics Laboratory (EESD), School of Architecture, Civil and Environmental Engineering (ENAC), Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland, katrin.beyer@epfl.ch

ABSTRACT
When testing multi-storey structures, most testing facilities require the testing of a reduced scale model. Previous work by other researchers revealed that scaling of masonry was not straightforward. For instance, differences in strength and elastic stiffness of the different sized masonry were reported. These distortions could be reduced but not eliminated by scaling the brick units and the thickness of mortar joints correctly. When addressing the seismic behaviour of structures, also the deformation capacity of the masonry is important, for which few comparative studies for different sized masonry could be found.

This paper presents selected results of two series of tests on URM piers that were constructed at full- and half-scale, respectively. The brick units of the half-scale masonry had half the size of the brick units of the full-scale masonry and similar mechanical properties. The head and bed joint thicknesses of the half-scale masonry were scaled accordingly and the same mortar mixture as for the full-scale masonry was used. Results from material tests and quasi-static cyclic tests on piers for the different sized masonry are presented and differences with regard to the force and displacement capacity are discussed.

KEYWORDS: scaling effects, unreinforced masonry, quasi-static testing, material testing

INTRODUCTION
A general problem in experimental testing of civil engineering structures is the size of the specimen: the examined structures are normally of such large dimensions (buildings, bridges, etc.) that it is usually impossible to test an entire structure at full-size. As a consequence, either only parts of the whole structure are tested or the models are scaled down to a maximum feasible size. Often, a combination of both is required to optimize the cost and the similitude to real size structures.

When small scale testing is chosen, the scaling affects the physical properties (stresses, displacements, acceleration, etc.). In order to draw correct conclusions from a reduced scale test, it is important to understand the different factors influencing the properties of the scaled structure. Several theoretical scaling models have been developed, which describe the ideal relations between the different scaled physical properties, e.g., [1, 2]. Herein, only the Artificial Mass Simulation [3, 4] shall be mentioned. This scaling approach is based on, first, using at reduced scale a material which has the same mechanical properties as the material for the equivalent full size prototype structure, and second, on compensating the distortions introduced by the scaling factor by adding an artificial mass.

According to Tomaževič and his co-workers, three similarities are important for obtaining a good match in the overall behaviour of small scale and full-scale masonry structures [5, 2, 6]: (1) the similarity in failure mechanism and damage pattern, (2) the similarity of the stresses and (3) the similarity in mass and stiffness distribution. The similarity in failure mechanism and damage pattern is important for a correct simulation of energy dissipation. However, in masonry, the failure is dominated by the stresses, which again depend on the masses and the stiffness distribution. The Artificial Mass Simulation fulfils the requirement of similarity in mass and stiffness and thus, similarity in stresses. However, it could be shown that in reality, it is rather difficult to obtain the same mechanical properties for the reduced scaled masonry material as for the prototype masonry material.

In the framework of a research project initiated by the Earthquake Engineering and Structural Dynamics Laboratory (EESD) at EPFL, Switzerland, and funded through the FP7 programme SERIES a shake table test on a 4-storey structure at half-scale is planned. The test itself will be performed at the TREES Laboratory in Pavia, Italy. The structure represents a typical Swiss residential apartment building which is composed of unreinforced (URM) and reinforced concrete (RC) piers and RC slabs. Because of the limited size of the shake table, the structure will be tested at half-scale. While it could be shown that concrete elements – when scaled properly – show similar behaviour at reduced scale as at full-scale, this is not the case for masonry. Thus, a correct simulation of the mixed structure requires correct scaling of the URM.

This article presents selected topics of an ongoing investigation on the scaling of masonry material. First, a brief overview is given of the upcoming problems when using reduced scale masonry. In the second part, recommendations for the choice of reduced scale bricks and mortar are given that aim at minimizing the differences between reduced and full-scale masonry. Finally, preliminary results of a testing campaign are summarized where the chosen reduced scale masonry is compared to a representative full-scale masonry. The testing campaign comprises material testing and a series of quasi-static cyclic tests on half- and full-scale masonry piers. The remaining differences are outlined and discussed.

LITERATURE REVIEW

Hilsdorf [7] estimates the masonry strength as a function of the brick and mortar strength:

$$U_U \cdot \frac{f_w}{f'_b} = \frac{1}{r_{b,m} + a_m \cdot r_{w,g}} \cdot \left(r_{b,m} + \frac{f'_m}{f'_b} \cdot a_m \cdot r_{w,g} \right) \tag{1}$$

with U_U being the non-uniformity coefficient at failure, f_w the compressive strength of the masonry unit, f'_b and f'_m the uniaxial strength of the brick and the mortar, a_m the coefficient of the influence of mortar under triaxial compression, $r_{b,m} = f_{b,t}/f'_b$ the brick material ratio ($f_{b,t}$ is the biaxial tensile strength of the brick) and $r_{w,g} = t_m/t_b$ the brick size ratio ($t_m$and t_b are the height of the mortar and brick) [8].

Egermann et al. [8] identified that when considering Equation 1 and using identical materials for the prototype and the reduced scale model (unit and mortar with identical strength and stiffness), the scaling factor should have a negligible influence on the compression strength of the masonry. A similar relationship was also developed for the E-modulus of the masonry [8, 7]. However, several studies using similar materials for prototype and model masonry have shown that the properties of the prototype and model masonry were rather different [6, 2, 9, 10, 8].

Reduced-sized model bricks can be manufactured in different ways: Replacing the model brick by a smaller brick of a different material proved to be complicated [6] and should be avoided, since it is difficult to quantify the exact distortions introduced by the different materials. The reproduction of solid model bricks at smaller sizes proved also to be complicated due to the burning procedure: the bricks burned at smaller size turned out to be stronger than prototype bricks [8, 11]. Another option is to cut the brick after the burning, e.g. [5]. However, in this case, the orientation of the loading should be equal to the one before cutting [10]. We also found that the roughness of the cut surface can differ considerably from the roughness of a brick which is wire-cut before the burning process. The recommendations in the literature only address solid clay bricks. When hollow clay units are scaled further properties, such as their anisotropic behavior, have to be considered. Hence, the void ratio and the effective width as well as the shape and the layout of the perforation need to be scaled properly.

The mortar joint is also affected by the scaling. In the literature it is often mentioned that the strength of the joint is influenced by the thickness of the joint, e.g. [12]. This difference is mainly due to the suction process, which happens when the dry brick gets in contact with the wet mortar. As a result the water-cement ratio of the mortar is reduced, which affects the mechanical properties of the mortar. The influence of the sucking behavior of bricks was investigated by several researchers. For instance, Brocken et al. [13] noted that pre-wetting of bricks affects the suction process only in a significant matter, if the water content of the brick reaches nearly saturation. Also the use of water retention products was found to be difficult: it is noted that the addition of water retention products does not influence the quantity of water extracted from the mortar but only slows down the suction process [13]. Moreover, only large quantities of water retention products showed a significant modification in the sucking behavior [14]. However, depending on the amount of adsorbed water, the strength of the masonry either increased or decreased [10] and thus, the effect on the strength is rather difficult to predict.

CHOICE OF THE REDUCED SCALE BRICK

According to the results from the literature review, we identified the following properties to be decisive for a good similitude between a reduced scale and a full-scale brick [15]: (1) similar material properties, (2) similar void ratio, (3) similar ratio of the sum of the web and shell thicknesses to the total width of the brick and (4) similar surface properties of the bricks in relation to the size of the aggregates in the mortar.

In order to fulfill the requirement of similar material properties, we identified that it was not only important to use the same initial clay material, but also to apply a similar burning procedure [15]. Hence, the web and shell thicknesses were kept identical and a similar ratio of the sum of the web and shell thicknesses to the total width of the bricks was ensured through reducing the number of webs. Figure 1 shows the chosen half- and full-scale brick and Table 1 shows the corresponding properties of both bricks.

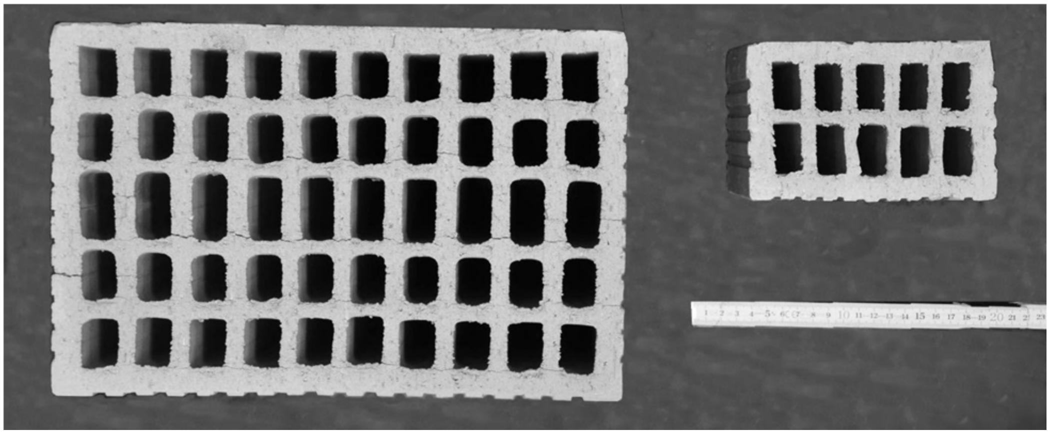

Figure 1: Final full- and half-scale brick from Morandi Frères SA, Switzerland

It can be noticed that small differences in void ratio and effective width remained, which resulted also in small differences in compression strength and average volumetric mass of the bricks. Also the tensile strength was about 5% higher for the half-scale brick than for the full-scale brick. Nevertheless, differences of brick strength were small compared to the variation of the results and the similarities between both bricks were considered satisfactory.

Table 1: Properties of the chosen bricks at half- and full-scale

		Full-scale brick	Half-scale brick
Average dimensions of a brick			
Length	mm	297	148
Width	mm	194	96
Height	mm	189	94
Average mass and density of a brick			
Mass / brick	kg	9.9	1.3
Volumetric mass	kg/m^3	901	996
Void ratios and effective length / width of a brick			
Void ratio	-	49.3	39.5
Effective length*)	-	30.6	37.8
Effective width*)	-	28.9	36.5
Average strength and deviation			
Compression, parallel to perforation	MPa	35.0 ± 7%	33.3 ± 25%
Compression, perpendicular to perforation	MPa	9.4 ± 8%	10.8 ± 17%
Tensile strength, perpendicular to perforation	MPa	1.27 ± 38%	1.61 ± 41%

*)The effective length / width describe the percentage of filled material to voids over the gross length / width.

CHOICE OF THE MORTAR FOR THE REDUCED SCALE JOINT

The literature review revealed the difficulties associated with scaling of the mortar joint thickness caused by the absorption of the water in the wet mortar by the dry brick. Thus, also the mortar joint needed to be investigated and one series of triplets at each scale was constructed and tested under uniform compression. Furthermore, two options to reduce the effect of the suction behavior at half-scale were studied through testing additional triplets at half-scale: (1) addition of a water retention product to the mortar and (2) fully saturation of the brick. The triplets were subjected to unidirectional compression. Results showed that some differences remained between the unmodified half- and full-scale masonry. However, these differences were not significantly reduced neither by adding a water retention product to the mortar nor by saturating fully the brick. Thus, it was decided to construct the half-scale masonry without modification of mortar or bricks but just to scale the size of the joints [15].

MATERIAL TESTS ON HALF- AND FULL-SCALE MASONRY

At the time of writing this paper, two types of material tests were performed: (1) compression tests on small masonry panels of 2 bricks x 5 layers and (2) shear tests on triplets of 1 brick x 3 layers. The different experiments are shown in Figure 2 and 3. In addition, diagonal tensile strength tests will be conducted. The specimens have been constructed but have not yet been tested.

For the compression tests, a series of five specimens was constructed at each scale and tested under uniform compression. The results are summarized in Table 2. Good similitude was obtained for the compression strength ($f_{u.M}/f_{u.P} = 0.96$) and the Poisson‘s ratio ($\nu_M/\nu_P = 1.0$). Nevertheless, the coefficient of variation of the Poisson’s ratio is rather large and, furthermore, for each series one specimen was not considered because the obtained value for Poisson’s ratio seemed unreasonable (see Table 2). The E-modulus was determined using the longitudinal average strain and stress at 1/3 of the maximum force. The Poisson’s ratio was determined at the same time through the lateral expansion. At both scales, the E-modulus varied significantly (see Table 2) and large differences between half- and full-scale were obtained ($E_M/E_P = 1.54$). SIA 266 [16], the Swiss code for masonry structures, estimates the E-modulus as:

$$E = 1000 f_u \tag{2}$$

Table 2: Results from the compression tests performed on half- and full-scale masonry wallettes.

	Wallette	f_u [MPa]	E_m [MPa]	E_m/f_u [-]	ϑ [-]
Half-scale	WUM1	5.81	3940	679	0.18
	WUM2	5.08	6890	1360	0.71*)
	WUM3	6.22	5940	954	0.22
	WUM4	6.10	4990	818	0.23
	WUM5	5.11	5560	1090	0.17
	Average	**5.66±4%**	**5460±8%**	**965±11%**	**0.20±6%**
Full-scale	WUP1	6.04	3210	533	-0.01*)
	WUP2	5.71	3640	637	0.33
	WUP3	5.62	4890	869	0.17
	WUP4	4.86	2830	583	0.20
	WUP5	7.07	3190	452	0.11
	Average	**5.87±5%**	**3550±9%**	**613±10%**	**0.20±19%**

*) This value was not considered for the computation of the mean value.

Therefore, the ratio between the measured E-modulus and the compression strength is given in Table 2. While a similar relationship to Equation 2 was found for the half-scale masonry, this is not the case for the full-scale masonry. At full-scale, the masonry was surprisingly soft.

At each scale, five shear triplet tests were carried out. In Figure 3 the test setup is shown for both scales. In Figure 4, the shear and normal stress versus the relative displacement is shown and, in Figure 5, the peak and the residual shear stress are given as a function of the normal stress. TUP1 (triplet unit 1 at prototype scale) and TUM5 (triplet unit 5 at model scale) failed due to local failure of the bricks at the supports. Therefore, both specimens were not considered in the evaluation of the cohesion and friction and are marked with a circle in Figure 5.

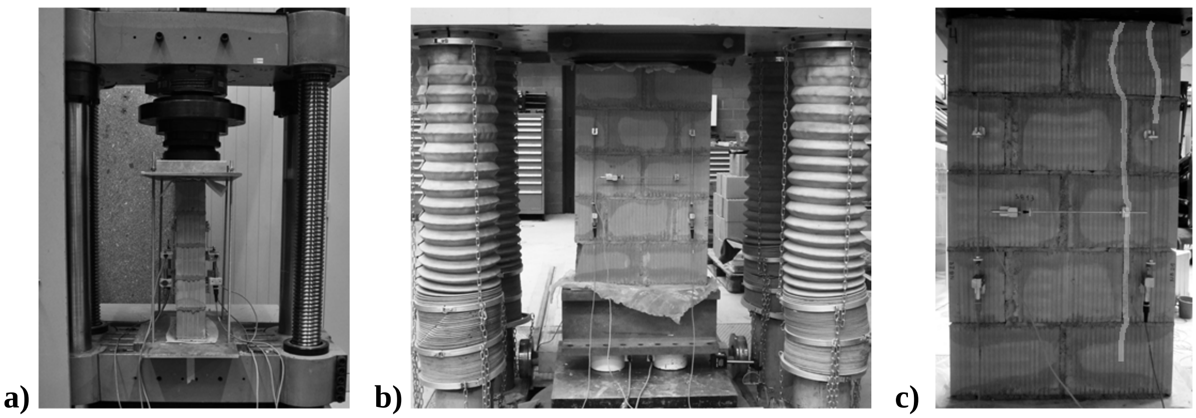

Figure 2: Half- and full-scale masonry wallettes under compression; (a) test setup for half-scale masonry wallettes, (b) test setup for full-scale masonry wallettes and (c) full-scale test specimen with vertical cracks after failure of the specimen.

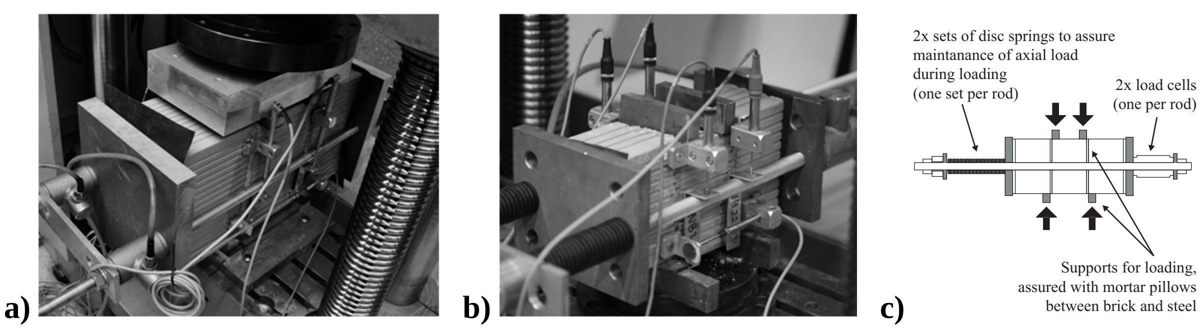

Figure 3: Shear tests, (a) full-scale triplet during testing, (b) half-scale triplet during testing, (c) schematic showing the test setup for the triplets.

When we compare the results from the half- and full-scale triplets, significant differences can be noticed: the cohesion of the half-scale masonry ($c_M = 0.2$MPa) is 25% lower than the cohesion of the full-scale masonry ($c_P = 0.27$MPa), while the friction coefficient is around 22% lower ($\mu_M = 0.71$MPa and $\mu_P = 0.91$MPa). For each series of triplets, three mortar samples were taken and tested under 3-point flexure and compression. The obtained mortar properties of the two series were very similar. Hence, the differences in the shear strength of the joint must have their origin elsewhere. Two possible reasons have been identified: One possible reason could be the scaling of the joint thickness. As outlined above, the size of the joint influences the curing of the mortar and thus the properties of the mortar-brick interlayer.

One further reason might relate to the scaling of the layout of the brick. The reduced size brick was scaled by reducing the number of webs, while keeping the web and shell thicknesses the same. Hence, the void ratio v of the half-scale brick was approximately 20% smaller than the void ratio of the full-scale brick ($v_M = 39.5\%$ and $v_P = 49.3\%$, see Figure 1 and Table 1). When we consider the local shear stress to be dominated by the shearing off of the mortar pillars – which develop when the mortar is pressed inside the voids of the perforated bricks – we find a correlation between the total surface of the mortar pillars $A_{perf} = vA_{tot}$ and the shear force $F_{sh} \sim A_{perf}$. The shear stress was previously computed by dividing the shear force F_{sh} by the gross area A_{tot} of the brick ($\tau = F_{sh}/A_{tot}$). The total area of the mortar pillar represents the area of the perforation A_{perf} in the brick and can be computed as a function of the void ratio v and the total area A_{tot} ($A_{perf} = vA_{tot}$). We find that the ratio of the joint shear strengths is approximately proportional to the ratio of the void ratios:

$$\frac{\tau_M}{\tau_P} = \frac{F_{sh,M}/A_{tot,M}}{F_{sh,P}/A_{tot,P}} \sim \frac{v_M}{v_P} = \frac{39.5\%}{49.3\%} = 0.80 \quad (3)$$

The joint shear strength when computed with respect to the perforated area is therefore approximately the same for the half- and full-scale masonry.

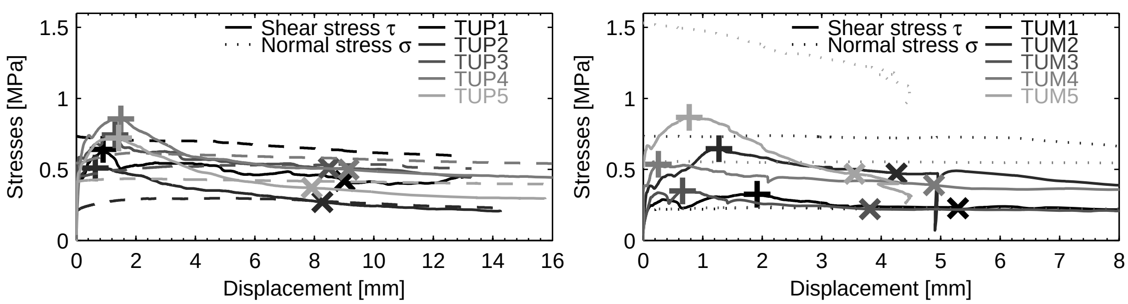

Figure 4: Average shear stress versus relative displacement between internal and external brick: (a) shear triplet tests performed on the full-scale masonry, (b) shear triplet tests performed on the half-scale masonry

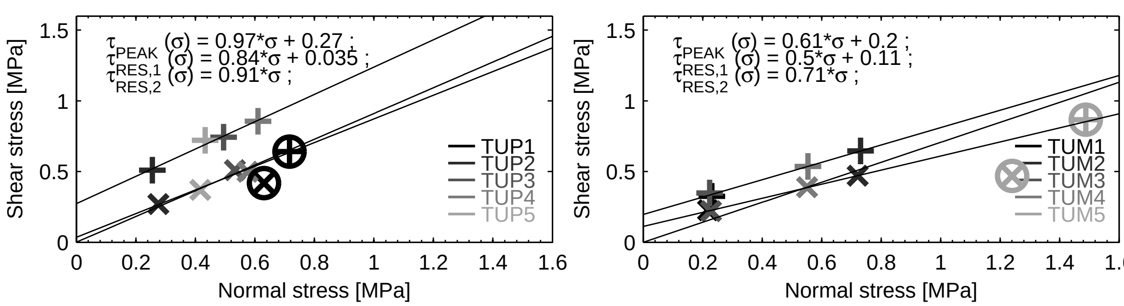

Figure 5: Peak and residual shear stresses versus normal stress: (a) shear tests performed on the full-scale masonry, (b) shear tests performed on the half-scale masonry

QUASI-STATIC CYCLIC TESTING OF PIERS AT BOTH SCALES

In the framework of a project investigating the influence of the boundary conditions on the displacement capacity of URM piers, three quasi-static cyclic tests on identical full size URM piers were performed [17]. All piers were subjected to the same vertical load but the boundary conditions for the lateral loading were varied. For the first pier, fixed-fixed boundary conditions with zero rotation at the top were simulated. For the second and third piers, the moment applied at the top of the pier was proportional to the applied horizontal load and therefore the height of zero moment was constant at 0.75 and 1.5 times the pier height H for the second and third pier, respectively (see Figure 6). In order to investigate the influence of scaling on the global force-deformation behaviour of such piers, these tests were repeated at half-scale. A picture of all six specimens after failure and a comparison of the hysteresis at full- and half-scale are shown in Figures 7 to 9.

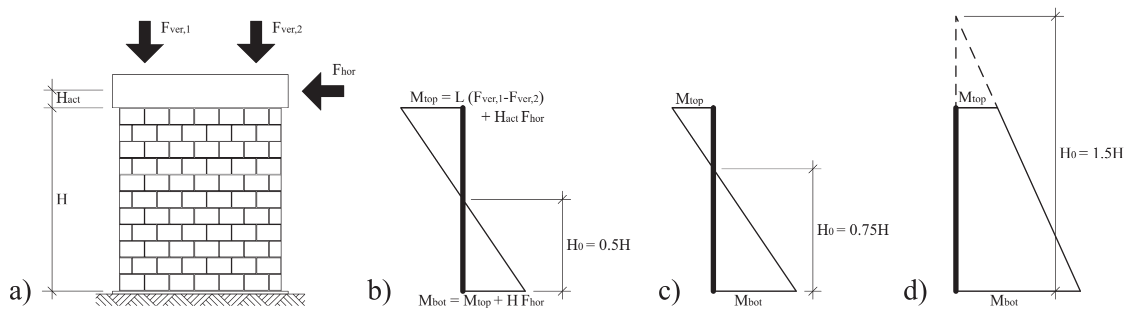

Figure 6: a) Schematic showing the boundary conditions for the URM piers with the resulting moment profile for b) PUM1/PUP1, c) PUM2/PUP2 and d) PUM3/PUP3

For all three pier configurations the tests on small scale masonry piers (PUM1 to PUM3, see Figure 7.b to 9.b) produced similar failure modes and failure patterns as the equivalent full-scale piers (PUP1 to PUP3, see Figures 7.c to 9.c): PUM1/PUP1 and PUM2/PUP2 showed a clear shear failure and PUM3/PUP3 showed a clear flexural failure. For PUM1/PUP1 – both tested under fixed-fixed boundary conditions – the resulting average shear strength and the initial stiffness were in good agreement. Also the displacement capacities matched quite well (see Figure 7.a). PUM2/PUP2 were tested at a constant zero moment height of 0.75 H. The agreement in terms of stiffness and strength was, however, less satisfactory as for the pair PUM1/PUP1 (see Figure 8.a): PUM2 was stiffer and stronger and failed earlier with a significant smaller displacement capacity than PUP2. For both, PUM3/ PUP3, the hysteresis curves were slightly asymmetrical for loading in positive and negative direction (see Figure 9.a) and the best match between PUM3 and PUP3 is reached when one of the two hystereses is plotted with inverse signs. In this case, an excellent match of initial stiffness and of average peak shear stress can be noticed. However, differences remained in the post peak behaviour.

Flexural resistance is normally controlled by the compression strength, thus, good agreement of PUM3/PUP3 is expected after obtaining similar compression strengths. PUM1/PUP1 and PUM2/PUP2 were dominated by shear behaviour. When we assume that this kind of failure is controlled by the shear strength of the joints, the good similitude between PUM1/PUP1 is somewhat surprising. However, for all piers failing in shear (PUM1/PUP1 and PUM2/PUP2), diagonal cracks propagated already at an early stage through the bricks. Hence, it is questionable whether the shear resistance of the piers is controlled by the shear strength of the joints.

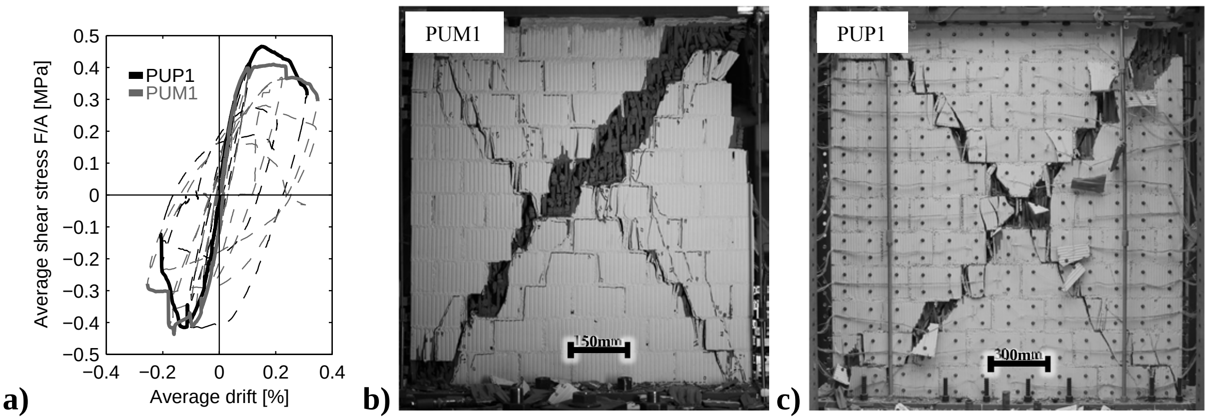

Figure 7: Comparison of the half-scale pier unit PUM1 and the full-scale pier unit PUP1 tested under fixed-fixed conditions, a) hysteresis with envelope of PUM1/PUP1 b) PUM1 after failure c) PUP1 after failure

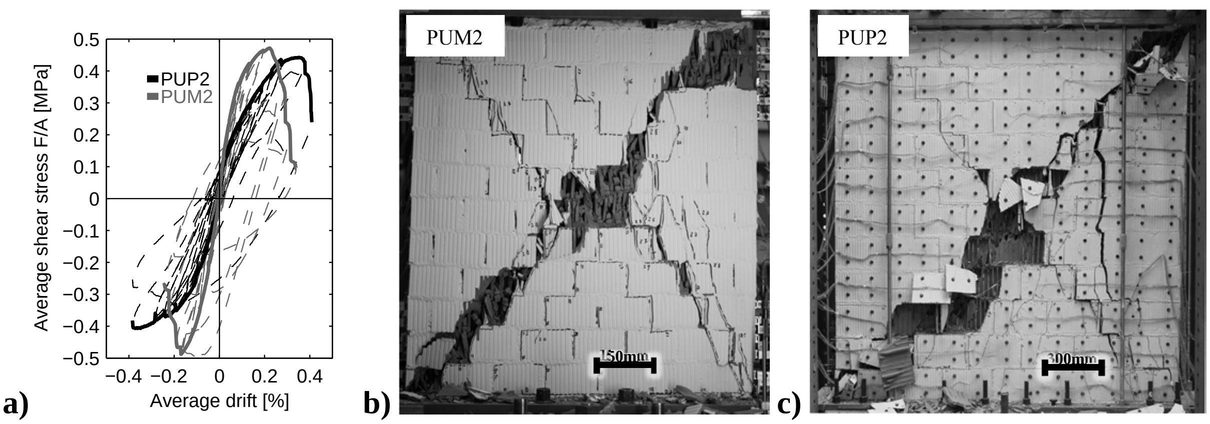

Figure 7: Comparison of the half-scale pier unit PUM2 and the full-scale pier unit PUP2 tested with a constant zero moment height of 0.75 H, a) hysteresis with envelope of PUM2/PUP2 b) PUM2 after failure c) PUP2 after failure

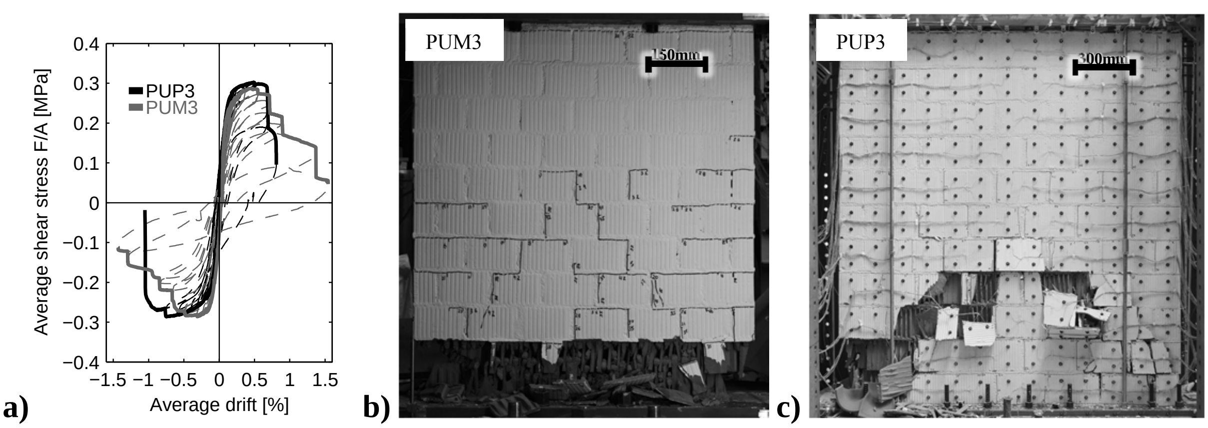

Figure 8: Comparison of the half-scale pier unit PUM3 and the full-scale pier unit PUP3 tested with a constant zero moment height of 1.5 H, a) hysteresis with envelope of PUM3/PUP3 b) PUM3 after failure c) PUP3 after failure

CONCLUSIONS AND OUTLOOK

A literature review revealed the difficulties associated with the scaling of masonry, which is often required when URM structures are tested in the laboratory. To reduce the differences between full-scale and small scale masonry, choosing the right components for the model masonry is essential. For a model masonry with hollow clay bricks for a shake table test on a four storey building tested at half-scale, we chose a model brick which was produced from the same clay and with the same manufacturing process as the prototype brick. Furthermore, the reduced scale brick had the correctly scaled cumulative web and shell thicknesses and had similar absolute thicknesses of each web and shell, i.e., the number of webs rather than the thickness of the webs was reduced. The exact quantification of the distortions introduced through the scaling of the mortar joint thickness remains still a difficult task. We decided to use the same mortar as for the prototype masonry and determined the remaining differences between small and full size masonry through different material tests on small masonry wallettes as well as quasi-static cyclic tests on piers.

Compression tests on masonry wallettes showed that the compression strength of the small scale masonry was very similar to the compression strength of the full-scale masonry. The compression strength of masonry is related to the tensile strength of the brick. Hence through the correct scaling of the bricks, the differences in compression strength of the masonry seemed to be minimized. Larger differences of approximately 20% were observed for the shear strength of the joint, which was determined through shear triplet tests. The shear strength of the joint is related to the mortar-brick interface which could have been affected by two factors: first, the void ratio of the full-scale and half-scale brick differed by approximately 20% and resulted in differences in the relative area of mortar pillars, which develop when the mortar is pressed inside the voids of the perforated bricks. Furthermore, the curing of the mortar is modified through the scaling of the joint thickness, hence, the interface properties are changed which might influence the cohesion and friction. However, preliminary comparison of quasi-static cyclic tests performed on three URM piers at full-scale and three URM piers at half-scale showed that globally good similitude between both masonries can be obtained. The failure mode was reproduced correctly for each specimen and also the initial stiffness and the peak strength could be captured correctly in two out of the three cases. The deformation capacity was more difficult to reproduce and was generally somewhat larger for the small scale piers. In ongoing work we compare the behaviour of the half- and full-scale piers subjected to quasi-static cyclic tests in more detail and on a larger set of piers and complete the comparison of the material properties of the half- and full-scale masonry.

ACKNOWLEDGEMENTS

The authors would like to thank Morandi Frères SA, Switzerland for the effort put into the production of the small scale bricks and for the donation of the small and full-scale bricks. Special thank is also due to Salvatore Marino for his help during testing of the reduced scale piers.

REFERENCES

[1] H. Krawinkler, “Possibilities and limitations of scale-model testing in earthquake engineering,” in *Proceedings of the Second US National Conference on Earthquake*

Engineering, Stanford, California, 1979, pp. 283-292.

[2] M. Tomaževič and T. Velechovsky, "Some aspects of testing small-scale masonry building models on simple earthquake simulators," *Earthquake Engineering and Structural Dynamics,* vol. 21, pp. 945-963, 1992.

[3] H. Krawinkler and P. D. Moncarz, "Similitude requirements for dynamic models," American Concrete Institute, Detroit, Michigan, 1982.

[4] P. D. Moncarz and H. Krawinkler, "Theory and application of experimental model analyis in earthquake engineering," The John A. Blume Earthquake Engineering center, Stanford, California, 1981.

[5] M. Tomaževič , P. Weiss, T. Velechovsky and C. Modena, "Seismic behaviour of masonry buildings - Shaking-table study of masonry buildings with different structural configuration - summary report, models 1,2,3 and 4," Ministry of Research Activity and Technology, Ljubljana, 1990.

[6] M. Tomaževič, "Dynamic modelling of masonry buildings: storey mechanism model as a simple alternative," *Earthquake Engineering and Structural Dynamics,* vol. 15, pp. 731-749, 1987.

[7] H. Hilsdorf, "Investigation into the failure mechanism of brick masonry loaded in compression," in *Designing, Engineering and Constructing with Masonry Products*, 1969, pp. 34-41.

[8] R. Egermann, D. Cook and A. Anzani, "An investigation into the behaviour of scale model brick walls," in *Proceedings of the Ninth international brick/block masonry conferences*, Berlin, Germany, 1991, pp. 628-635.

[9] P. Taunton, "Centrifuge modelling of soil/masonry structure interaction," Cardiff, United Kingdom, 1997.

[10] A. Mohammed, "Experimental comparison of brickwork behaviour at prototype and model scales," PhD thesis, Cardiff, United Kingdom, 2006.

[11] A. Mohammed, T. Hughes and A. Mustapha, "The effect of scale on the structural behaviour of masonry under compression," *Construction and Building Materials,* vol. 25, pp. 303-307, 2011.

[12] R. G. Drysdale and A. A. Hamid, Masonry structures - Behavior and design, 3rd ed., Bolder, Colorado: The Masonry Society, 2008.

[13] H. Brocken, M. Spielmann, L. Pel, K. Kopinga and J. Larbi, "Water extraction out of mortar during brick laying," *Materials and Structures,* vol. 31, pp. 49-57, 1998.

[14] K. Green, M. Carter, W. Hoff and M. Wilson, "The effects of lime and admixtures on the water-retaining properies of sement mortars," *Cement and Concrete Research,* vol. 29, pp. 1743-1747, 1999.

[15] S. Petry and K. Beyer, "Testing unreinforced masonry structures at reduced scale," in *Proceedings of the 15th World Conference of Earthquake Engineering*, Lisbon, 2012.

[16] SIA, *SN 505 266:2003 Masonry,* Zürich: Swiss Society of Engineers and Architects, 2005.

[17] S. Petry and K. Beyer, "Influence of the boundary conditions on the displacement capacities of URM piers," in *Proceedings of the 12th Canadian Masonry Symposium*, Vancouver, 2013.